GUN MUZZLE BLAST FIELD: A COMPUTATIONAL METHOD BASED ON THE UNIFIED THEORY OF EXPLOSIONS

FINAL REPORT

by

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3 February, 1978

U. S. ARMY RESEARCH OFFICE

DAAG29-77-G-0176

Department of Engineering Sciences
University of Florida
Gainesville, FL

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) 18 ARO 19 15359.1-A-E

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. ~~TITLE (and Subtitle)~~ 6
GUN MUZZLE BLAST FIELD: A COMPUTATIONAL METHOD BASED ON THE UNIFIED THEORY OF EXPLOSIONS.

5. TYPE OF REPORT & PERIOD COVERED 9
Final rept.

6. ~~PERFORMING ORG. REPORT NUMBER~~

7. AUTHOR(s) 10
Dennis R. Keefer

8. CONTRACT OR GRANT NUMBER(s) 15
DAAG29-77-G-0176

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Department of Engineering Sciences
University of Florida
Gainesville, FL 32611

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
U. S. Army Research Office
Post Office Box 12211
Research Triangle Park, N.C. 27709

12. REPORT DATE 11
3 Feb [redacted] 78

13. ~~NUMBER OF PAGES~~ 12 34p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
NA

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Muzzle Blast
Blast Field Around Guns
Gun Blast
Explosion Theory

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A computational method of Henriksen and Cummings based on Porzel's Unified Theory of Explosions has been extended to permit calculations of the blast field around gun muzzles. The theory has been extended to permit calculation of the blast field in the region behind the muzzle exit plane, and uses a different method for the prediction of overpressure pulse lengths. Predictions based on the theory were compared with experimentally determined values of overpressure and pulse lengths for guns from 8 inch diameter to .30 caliber. The theory was found to be adequate for

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

410049

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1. INTRODUCTION

The muzzle blast associated with the firing of a gun can be of sufficient magnitude to cause considerable damage to structures or personnel some distance away from the muzzle. Analytical methods of predicting the characteristics of the blast field are of primary importance to the analysis of a weapon system to insure structural integrity and personnel safety. Ideally, the analytical methods should be based on basic principles so that the blast field can be calculated without resort to empirically determined parameters.

Westine[1] has applied the technique of dimensional analysis to the blast field and, based on the examination of large quantities of experimental data, he presents empirical formulas for the prediction of blast overpressure, pulse length and time-of-arrival. The numerical constants in his equations are given for several barrel elevation angles together with a coefficient which determines the effective energy release for several propellents.

A completely different approach for the prediction of blast fields has recently been devised by Henriksen and Cummings[2]. Their analysis utilizes the Unified Theory of Explosions (UTE) developed by F. B. Porzel[3] in the course of an extensive study of nuclear and HE explosions. In their theory Henriksen and Cummings (HC) apply basic principles to evaluate the fraction of propellent energy which is available to the blast field and then use UTE to describe the propagation of the blast with distance. A function was derived to correlate the nonspherical muzzle blast field to the spherical blast field predictions of UTE.

In the present study the basic approach of HC has been retained, but the method of calculating the equivalent hydrodynamics yield has been modified; the non-spherical nature of the gun muzzle blast field has been included in UTE and a completely new method of calculating pulse length has been developed.

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1. *P. S. Westine and J. C. Hokanson, "Prediction of Stand-Off Distances to Present Loss of Hearing from Muzzle Blast", R-CR-75-003 Southwest Research Institute, February, 1975. Ad/A-005 274.*

2. *B. B. Henriksen and B. E. Cummings, "An a priori Theory for Muzzle Blast Overpressure and Pulse Length Determination", BRL*

3. *F. B. Porzel, "Introduction to a Unified Theory of Explosions(UTE)", NOL 72-209, US Naval Ordance Laboratory, White Oak, Silver Spring, MD, September, 1972. AD 758000.*

II. THEORY

A. Porzel's Unified Theory of Explosions

Both HC and the present development depend heavily on the theory and computational methods of Porzel's UTE[3]. This theory was developed over a period of time and appeared in a number of company and laboratory reports. A fairly comprehensive review of this theory appears in Reference 2 and only a brief synopsis will be presented here.

The UTE is strongly dependent on the separation of the total available energy into "prompt energy" which is available to drive the blast and delayed energy. The prompt energy includes the energy due to static overpressure and dynamic pressure and also includes the kinetic energy due to material velocity. The remaining energy in the explosive is delayed, meaning that it is transported too slowly to support the blast.

This division of energy removes some of the mathematical difficulties associated with the initial instant of energy release and permits an accurate calculation of the prompt energy remaining in the blast wave as it spreads outward and decreases in strength. The basic scaling is encompassed in the QZQ hypothesis which states

$$QZ^q = \text{constant} \tag{1}$$

where Q is the delayed energy (or waste heat), Z is a radial coordinate corrected for the mass of the explosion and q is a constant over a wide range of explosions having the ideal values of 3.5 for strong shocks and 4.0 for weak shocks. If the prompt energy remaining in the blast is known for any blast radius then the entire blast field can be scaled using Equation (1).

The blast overpressure at any radial location can be determined once Q(Z) is known. Porzel[3] derives an expression for Q as a function of overpressure based on the Rankine-Hugoniot equations and a generalized equation of state (GES). He also gives a binomial expansion for very low overpressures and an empirical relation for very high overpressures.

The scaling embodied in Equation (1) has been highly successful in predicting the blast field for spherical explosions from one pound of TNT to nuclear explosions. Application of the QZQ hypothesis to gun muzzle blast is complicated by two factors: calculation of the equivalent explosion strength or hydrodynamic yield and the high degree of asymmetry of the blast field compared to a sperical explosion.

B. Equivalent Hydrodynamic Yield for a Gun Muzzle Blast

A central concept in UTE is the division of the explosion energy

into prompt energy which supports the blast wave and delayed energy which does not. The prompt energy includes the energy due to static overpressure and dynamic pressure and also includes the kinetic energy due to material velocity. For a gun the prompt energy available to support the blast is a small fraction of the total propellent energy. A significant fraction of the propellent energy is used to impart kinetic energy to the projectile. Of the remaining energy a significant portion is lost in turbulent boundary layer generation in the gun barrel and impedance of the flow by the tube roughness.

In the previous application of UTE to the muzzle blast problem Henriksen and Cummings have analyzed the barrel loss processes and have shown, based on arguments first advanced by Porzel, that of the remaining energy only one-sixth is prompt energy which can support the blast waves. In their analysis Henriksen and Cummings did not include the kinetic energy of the moving charge in the determination of hydrodynamic yield, but included the directed kinetic energy in their treatment of the non-spherical nature of the blast field.

In the present analysis the kinetic energy of the moving gas at the instant the projectile leaves the barrel is included in the hydrodynamic yield. The initial prompt energy is

$$Y_o = \frac{1}{6}\{(M_p\varepsilon - KE)\beta + \frac{1}{2}M_pV_m^2\} \qquad (2)$$

where M_p is the propellent mass, ε is the specific energy of the propellent, KE is the projectile kinetic energy, β is the barrel loss factor as given by the HC theory and V_m is the muzzle velocity. An initial value of the explosion radius is required in addition to the initial prompt energy in order to use the QZQ hypothesis to predict blast overpressures. For the gun muzzle blast, the initial explosion may be considered as the mass of high pressure gas which exists the muzzle immediately after the projectile has left the muzzle. Schlieren photographs taken at these times show a "barrel shock" system whose characteristic size is of the order of two muzzle diameters. Hence, in the present analysis the barrel diameter is taken as the initial radius. Further, the QZQ scaling is relatively insensitive to the initial radius chosen.

C. The Non-spherical Geometry

Experimental measurements of the blast fields produced by guns have shown that for a fixed distance from the observer to the muzzle, considerably larger overpressures occur in the region foreward of the muzzle than in the region behind the muzzle. This is analogous to the moving charge effect which has been studied by Armendt and Sperrazza[4].

4 *B. F. Armendt and J. Sperrazza, "Air Blast Measurements Around Moving Explosive Charges, Part III", BRL Memorandum Report No. 1019, U. S. Army Ballistic Research Laboratories Aberdeen Proving Ground, MD, July, 1956.*

They found that the blast from a moving charge remained essentially spherical about an origin which moved with the center of mass of the decelerating charge. The deceleration of the charge could be determined by conservation of momentum. The center of mass decelerates rapidly as the expanding shock wave engulfs an ever-growing mass of initially stationary air.

Detailed calculations were made based on this effect and while it predicts higher overpressures forward of the muzzle than aft, the effect is too small to explain the order of magnitude differences which are observed in the muzzle blast experiments. This is due, primarily, to the rapid deceleration of the center of mass which is produced by a rapidly expanding spherical shock.

Porzel[3] described a concept called generalized divergence (GDV) which permits an extension of UTE to non-spherical geometries. He notes that the physical significance of the spatial coordinate in the hydrodynamic equations is a radius of curvature rather than the location relative to some earlier position. It is the local radius of curvature of the wave front which determines its divergence. Thus it is the initial shape of the charge which determines the shape of the blast field.

The initial charge for a gun muzzle blast is the barrel gases which exit when the projectile leaves the muzzle. The high overpressure of these gases causes a "barrel shock" system to form as shown schematically in Figure 1. This provides an initial source for the blast field which is far from spherical. The local radius of curvature is much greater in the foreward portion of the shock system resulting in a smaller divergence and less rapid decrease in the blast overpressure forward of the gun muzzle compared to the rear where the radius of curvature is much smaller.

The concept of GDV was incorporated into the scaling of blast overpressure provided by the QZQ hypothesis by modifying the distance scale at each angular position in the blast field to correct for the initial non-spherical geometry. The value of R used in the QZQ calculation was given by

$$\bar{R} = R(\theta)/G(\theta) \tag{3}$$

where $G(\theta)$ is a geometry factor which was determined on an *ad hoc* basis. It was found that the experimental data were reasonably well represented using a geometry factor given by

$$G(\theta) = \frac{3}{4}[\cos\theta + \sqrt{\cos^2\theta + (4/3)^2}] \tag{4}$$

The derivation of this function was based on a velocity argument and is given in Appendix A.

To summarize, the calculation of overpressure for gun muzzle blast was accomplished by the following sequence:

1. Calculate the initial hydrodynamic yield using Equation (2).
2. The hydrodynamic yield was used to determine the constant in the scaling law, Equation (1).
3. At a given position (distance and angle) in the blast field the value of Q was computed from Equation (1) using a value of R determined from Equations (3) and (4).
4. The blast overpressure at the given field position was determined from the value of Q determined in step 3 using the relations given by Porzel[3].

D. Pulse Length Calculations

Henriksen and Cummings[2] determined the pulse length of the overpressure pulse based on a characteristic length and the particle velocity. The characteristic length was representative of the volume occupied by the remaining prompt energy in the blast.

An alternate method of calculating the pulse length has been developed based on the propagation of waves of finite amplitude. As the blast wave from the explosion expands, the initial high overpressure at the shock front decreases behind the shock front. At some point in the expansion, designated the transition radius, the overpressure behind the shock drops to zero and upon further expansion the blast wave develops a negative phase[5]. The fluid velocity behind the shock has a similar behavior with a large velocity in the direction of the shock velocity decreasing to zero and becoming negative. The resulting pulse forms are shown in Figure 2. These pulses of finite amplitude propagate into the undisturbed air. The propagation velocity is not the same for all portions of the pulse, but depends on the local speed of sound and the fluid velocity. The leading edge of the pulse propagates with a greater velocity than the rest of the pulse and therefore the pulse increases in length as it propagates outward.

The local wave speed for the pulse of finite amplitude is given by[6]

$$c = a_n + u \tag{5}$$

where a_n and u are the local value of the speed of sound and fluid velocity. For an isentropic process the local wave speed becomes

$$c = a + \frac{\gamma+1}{2} u \tag{6}$$

where a is the speed of sound in the undisturbed region ahead of the

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5. *Yu.B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, Vol. 1 Academic Press, New York, 1966.*
6. *H. W. Liepmann and A. Roshko, Elements of Gasdynamics, John Wiley and Sons, New York, 1957.*

pulse. The propagation of a shock is not an isentropic process, but for overpressures at distances greater than the transition radius the corrections are small compared to the uncertainty in the measured values.

The trajectories of the pulse front and the point at which the fluid velocity drops to zero are shown in Figure 3. The pulse shape is shown at the transition radius r_o and at two other positions.

We will define the pulse length τ as the time between these two trajectories at a given position r. Note that as the shock wave expands and the fluid velocity behind the shock approaches zero, the shock front approaches the speed of sound and the pulse length approaches an asymptotic value which then propagates as an acoustic wave.

The zero-velocity trajectory is given by

$$t_1 = \frac{1}{a}(r - r_o) + t_o + \tau_o \tag{7}$$

and the shock front velocity by

$$t_2 = \frac{1}{a}\int_{r_o}^{r} \frac{dx}{1 + \frac{\gamma+1}{2}\frac{u}{a}} + t_o \quad . \tag{8}$$

The difference of these expressions gives the pulse length

$$\tau = \tau_o + \frac{1}{a}\left[(r-r_o) - \int_{r_o}^{r} \frac{\quad}{1 \quad - \cdot\frac{u}{a}}\right] \tag{9}$$

where τ_o is the initial pulse length at the transition radius r_o. The initial pulse length τ_o can be estimated with the aid of Figure 4 which shows the overpressure at the time t when the shock reaches the transition radius[7]. This is the radius for which the negative phase has fully developed and occurs at a pressure ratio of two across the shock. If we make the *ad hoc* assumption that the pulse occupies half the spherical radius at transition then the characteristic initial pulse length is given by

$$\tau_o = \frac{r_o}{2c_s} \tag{10}$$

where c_s is the wave speed of the shock at a pressure ratio of two.

The pulse length is calculated from Equation (9) using the initial pulse length given in Equation (10) and the fluid velocity determined

7. *H. L. Brode, "Numerical Solutions of Spherical Blast Waves", J. Appl. Phys., Vol. 26, No. 6, June 1955, pp. 766-775.*

from the Rankine-Hugoniot relations[7] and the local value of overpressure determined from UTE.

III. RESULTS

The purpose of this study was to determine the applicability of the Henriksen and Cummings theory for smaller caliber guns and to extend the analysis to include those positions aft of the muzzle exit plane. The theory has been applied to predict muzzle blast overpressure for guns ranging from an 8 inch diameter naval gun to a .30 caliber pistol. The predictions of the theory have been compared to the data of Westine[8] and the results are presented in Figures 5 through 9.

The theory is clearly capable of predicting the muzzle blast overpressure for guns of vastly different calibers. Careful examination of the curves shows that the theory will also predict the angular variations in the blast field with reasonable accuracy over the full range of calibers examined. The largest discrepency between theory and experiment occurs at distances beyond 50 calibers where the experimental data exceeds the theoretical predictions. The experimental data were all obtained with the guns firing essentially horizontally over the ground or a ground plane. The shock wave associated with the muzzle blast will reflect from this plane causing a reinforcement to the primary shock which increases the measured overpressure. Indeed, in much of the data the measured overpressure values increase with increasing distance from the muzzle for distances beyond 50 calibers. Since the theory does not account for reflected shocks the disagreement at large distances is not surprising.

Examination of the angular behavior of the theory for distances less than 50 calibers for the cases considered reveals that on the average the theoretical predictions tend to overestimate the overpressure in the aft (greater than 90°) portion of the blast field and underestimate the overpressure in the foreward portion of the field. This is particularly noticeable for the .30 caliber pistol, the smallest gun considered. This effect is a result of the particular form of the geometry factor chosen. An improvement might be obtained by modifying the form of the geometry factor according to the ratio of random to ordered motion in the muzzle gases as proposed in Reference 2.

Since the current theory contains the kinetic energy of the muzzle gas in the prompt energy the overpressure was calculated for a 105 mm gun in which the muzzle velocity varied as a result of different propellent charges. The results are shown in Figure 10. The theory

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8. *P. S. Westine, "Modeling the Blast Field Around Naval Guns and Conceptual Design of a Model Gun Blast Facility," TR 02-2643-01 Southwest Research Institute, September,1970, AD 875 984.*

accurately predicts muzzle blast overpressure for these cases although the muzzle velocity is higher by a factor of two for the zone 8 (Z8) compared to the zone 5 (Z5) experiment. The result shows that the theory will predict the muzzle blast from guns over a considerable range of muzzle velocity.

Pulse length of the overpressure pulse is more difficult to compare since there are large variations in the experimental values obtained. A typical situation is shown in Figure 11 for the case of the same 20 mm gun shown in Figure 7. The theory predicts that the pulse length will increase with distance from the muzzle until it reaches some asymptotic value but the experiments often show that the pulse length first increases then decreases with distance. This decrease first appears at distances greater than 50 calibers and may be related to the shock reflection from the ground plane which produces pulses of complex shapes.

Predicted pulse lengths for four guns ranging from an 8 inch naval gun to a .30 caliber rifle are shown in Figure 12. The pulse length was calculated for an angle of 90° to the line of fire and the experimental data were taken at 75° and 105°. The measured values of pulse length are reasonably well predicted by the theory over the wide range of pulse lengths produced by guns of greatly different caliber.

These results indicate that the current theory gives reasonable agreement with experiment over a wide range of gun calibers. The theory has the advantage of simplicity and ease of calculation and should be of great value in the prediction of free-field gun muzzle blast effects.

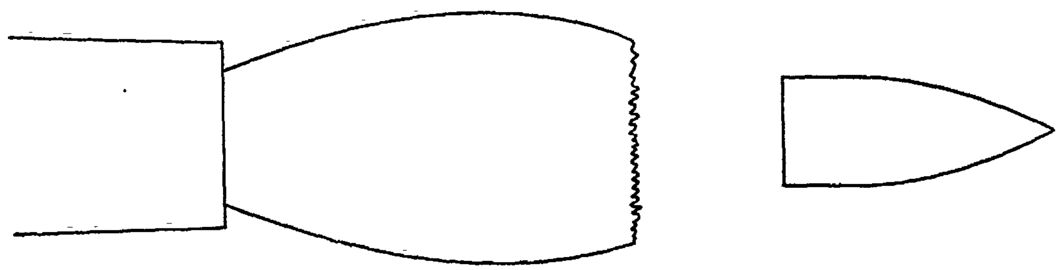

FIGURE 1. "Barrel Shock" Produced by Propellent Gases Exiting Muzzle.

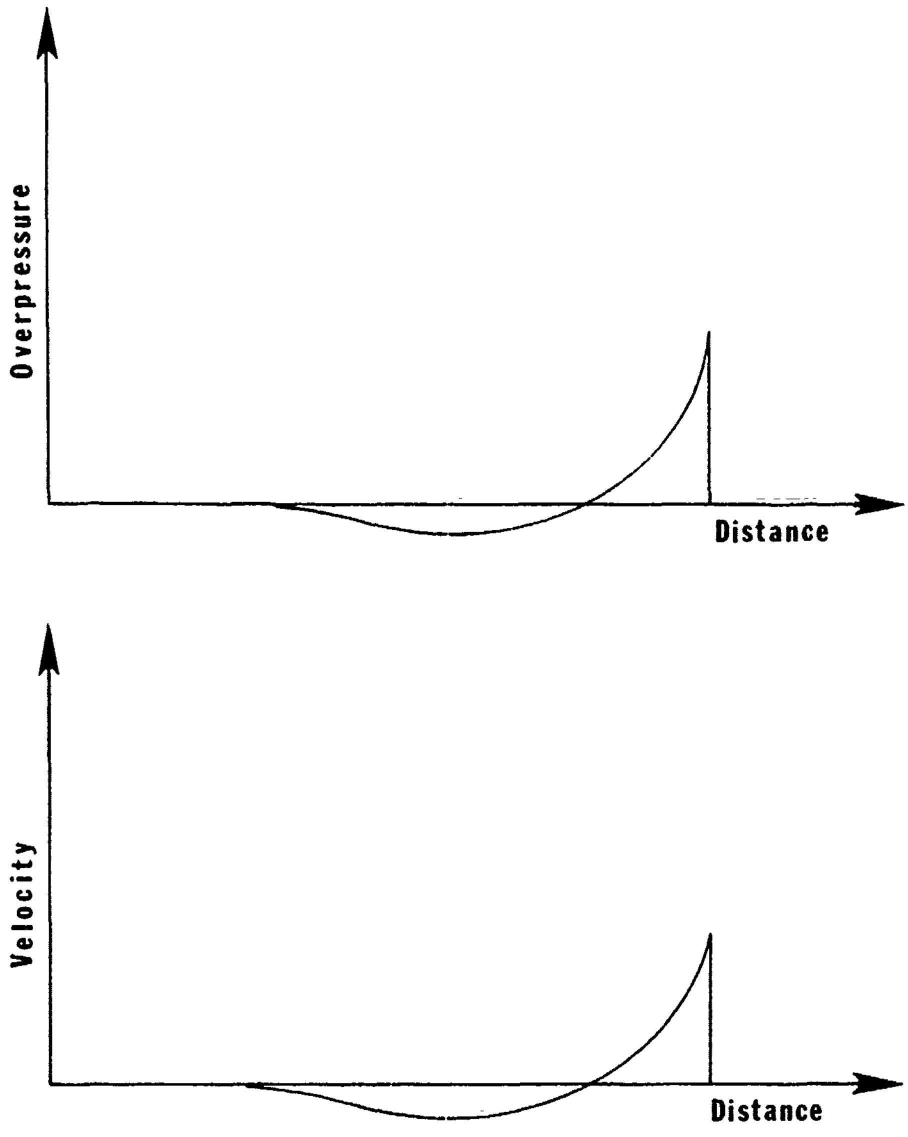

FIGURE 2. Sketch of Overpressure and Fluid Velocity in the Blast Pulse After the Negative Phase Has Developed.

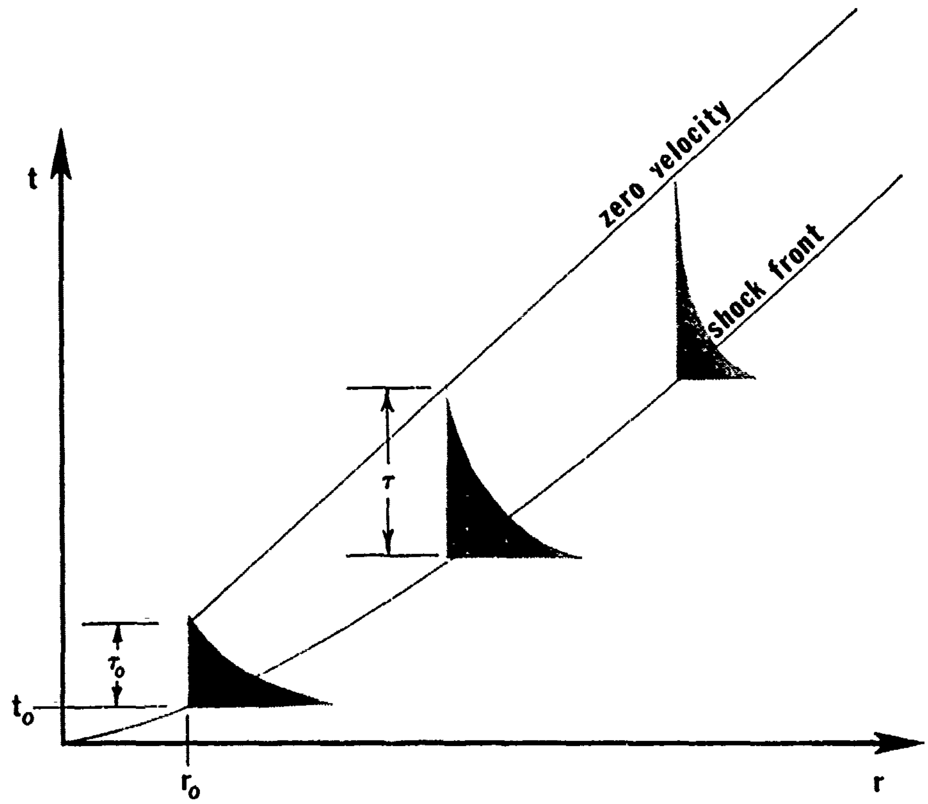

FIGURE 3. Sketch of the Trajectories of the Pulse Front and the Point Where Fluid Velocity Drops to Zero.

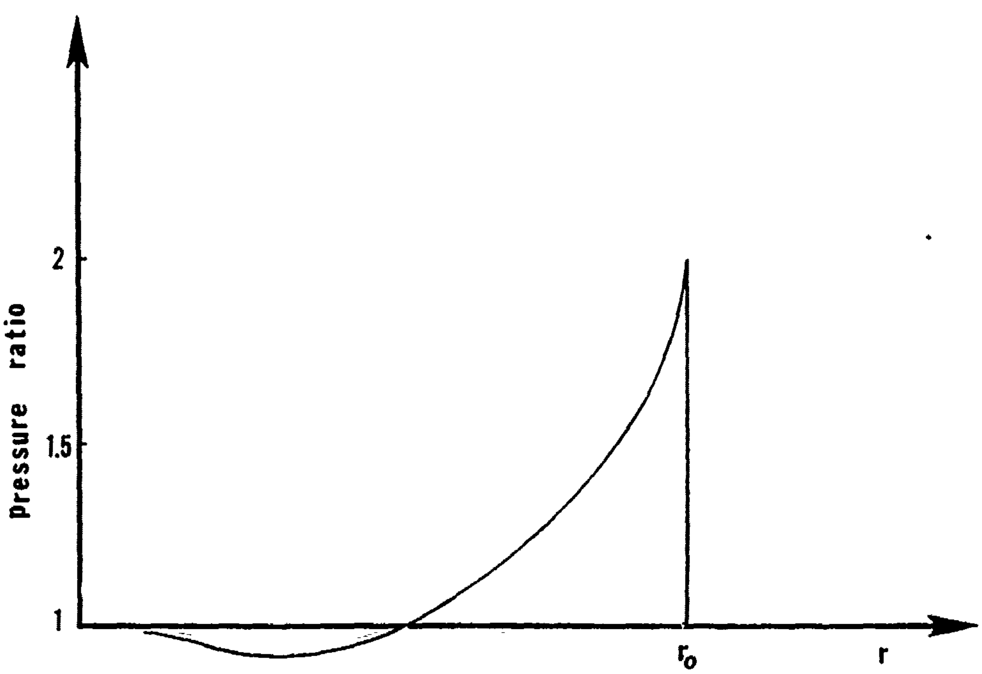

FIGURE 4. Overpressure Pulse at Transition. The Pressure Ratio Drops to Unity of Approximately One-Half the Transition Radius r_o.

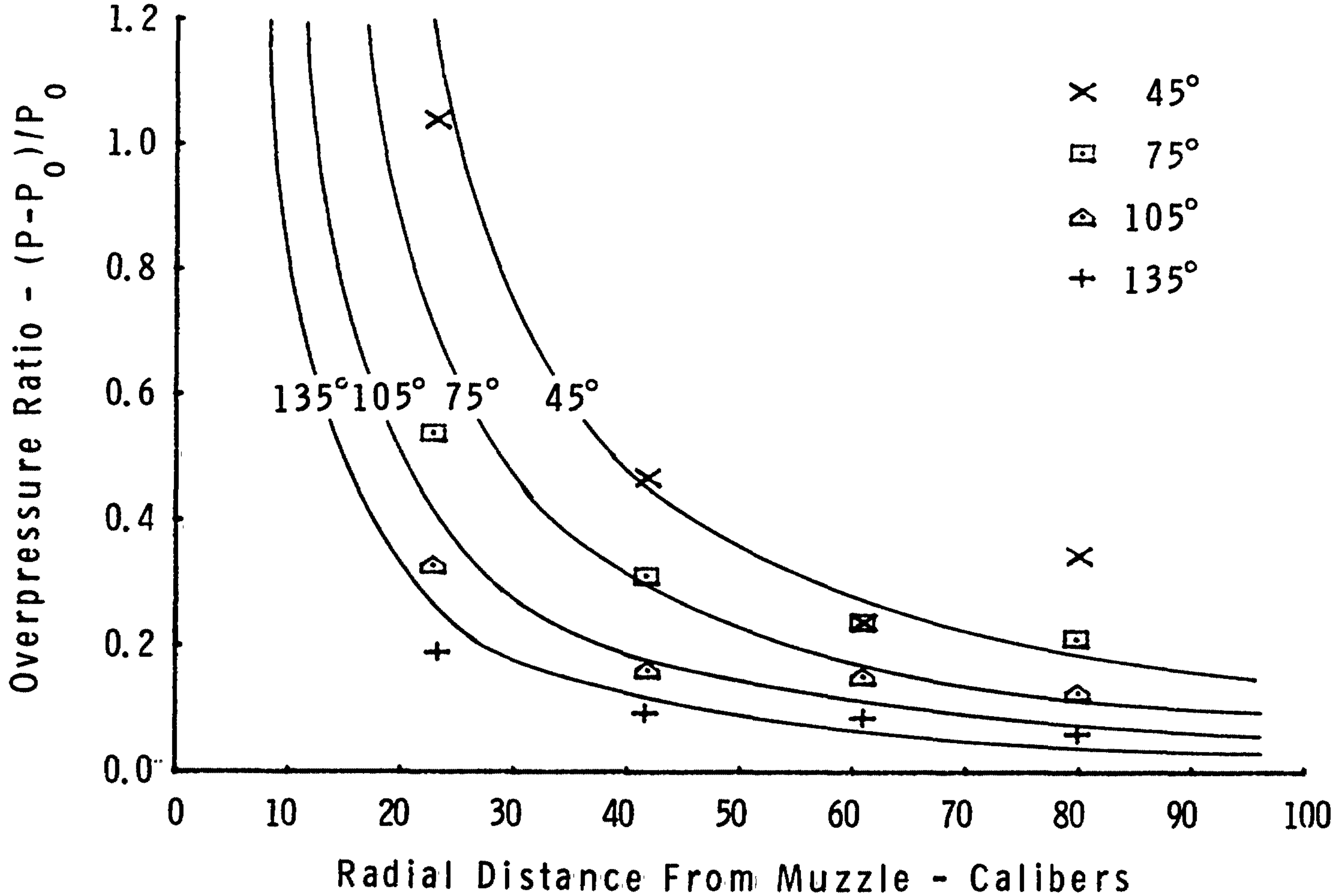

FIGURE 5. Overpressure from 8 inch Naval Gun.

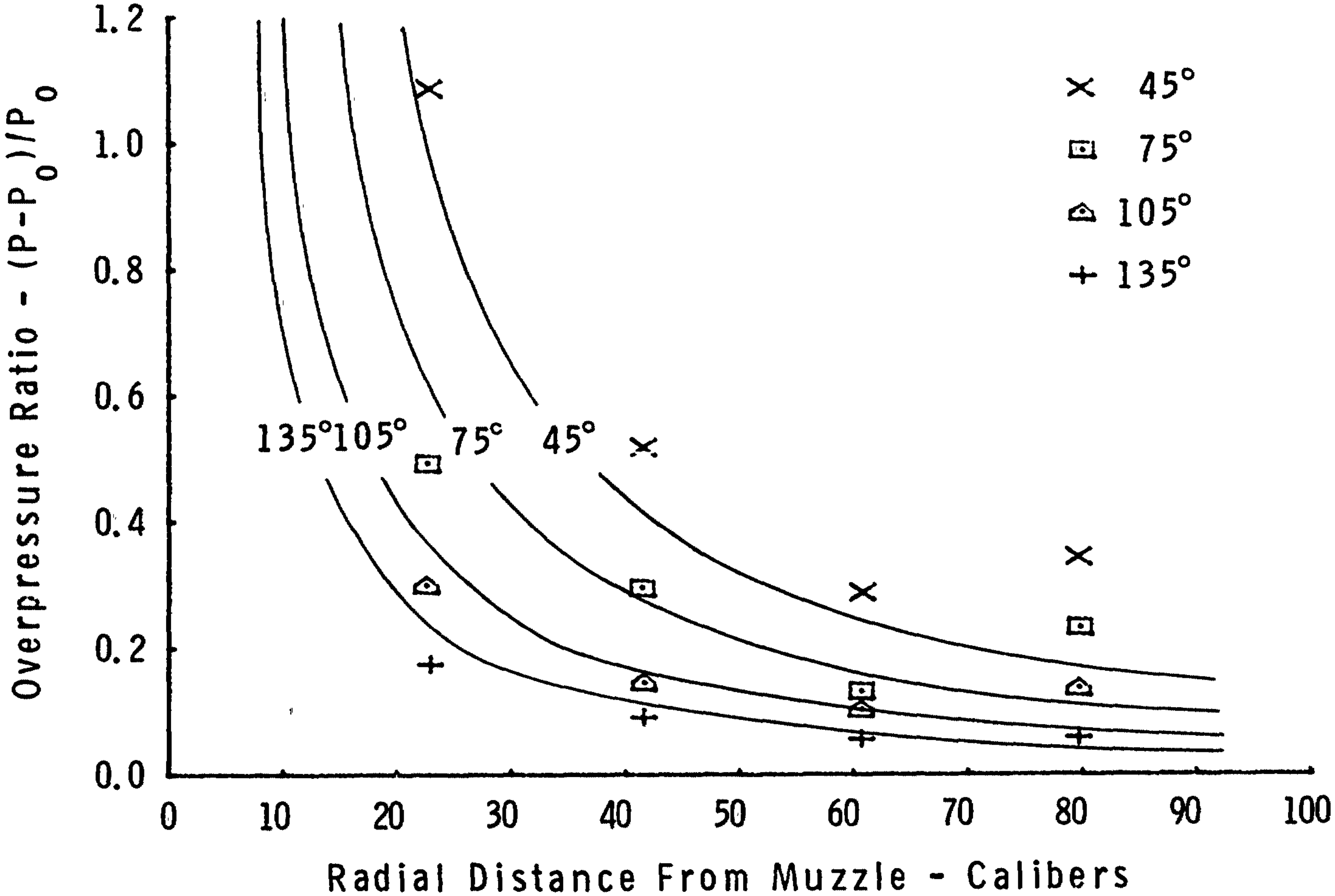

FIGURE 6. Overpressure from 3 inch Naval Gun.

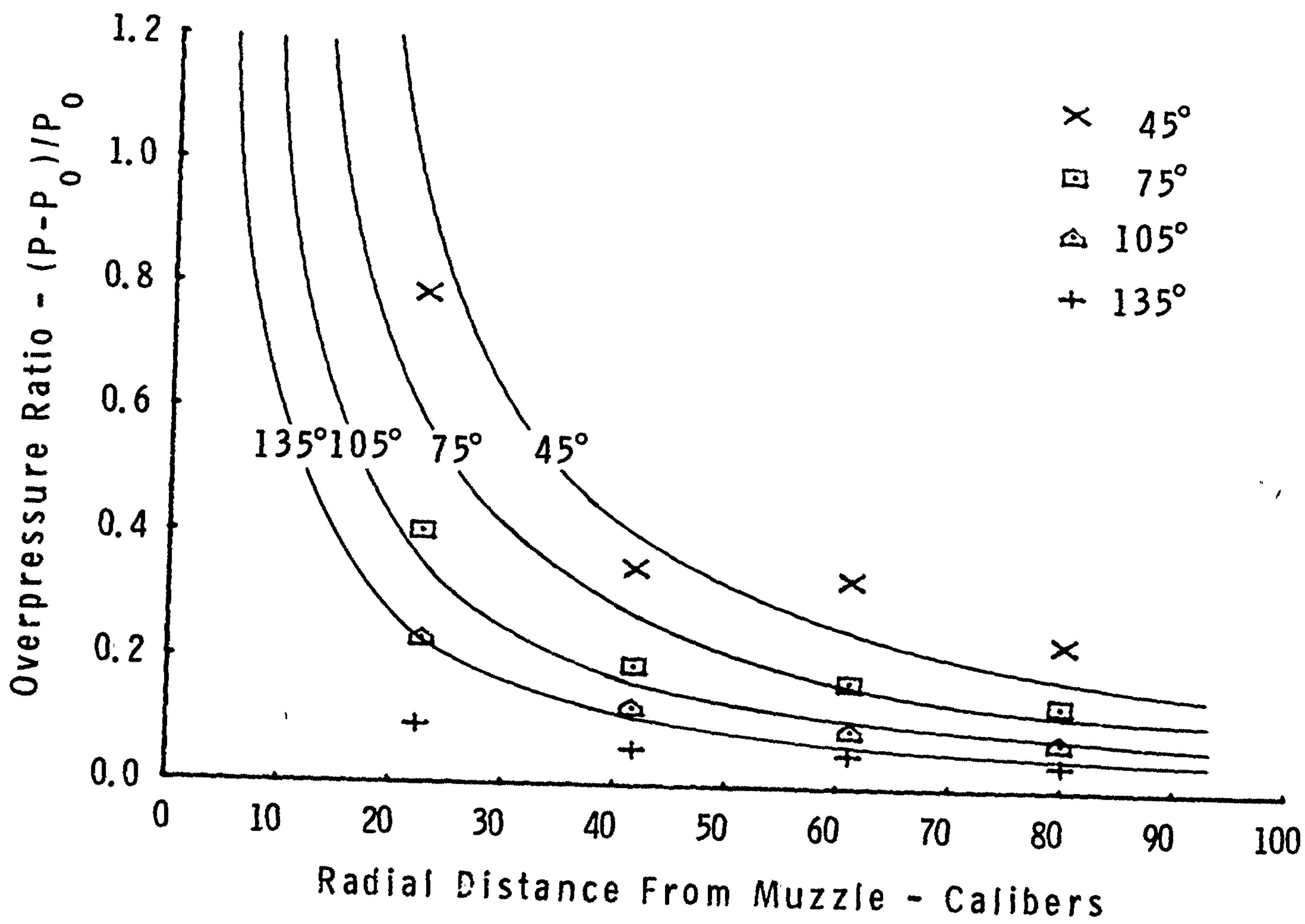

FIGURE 7. Overpressure from 20 mm Gun.

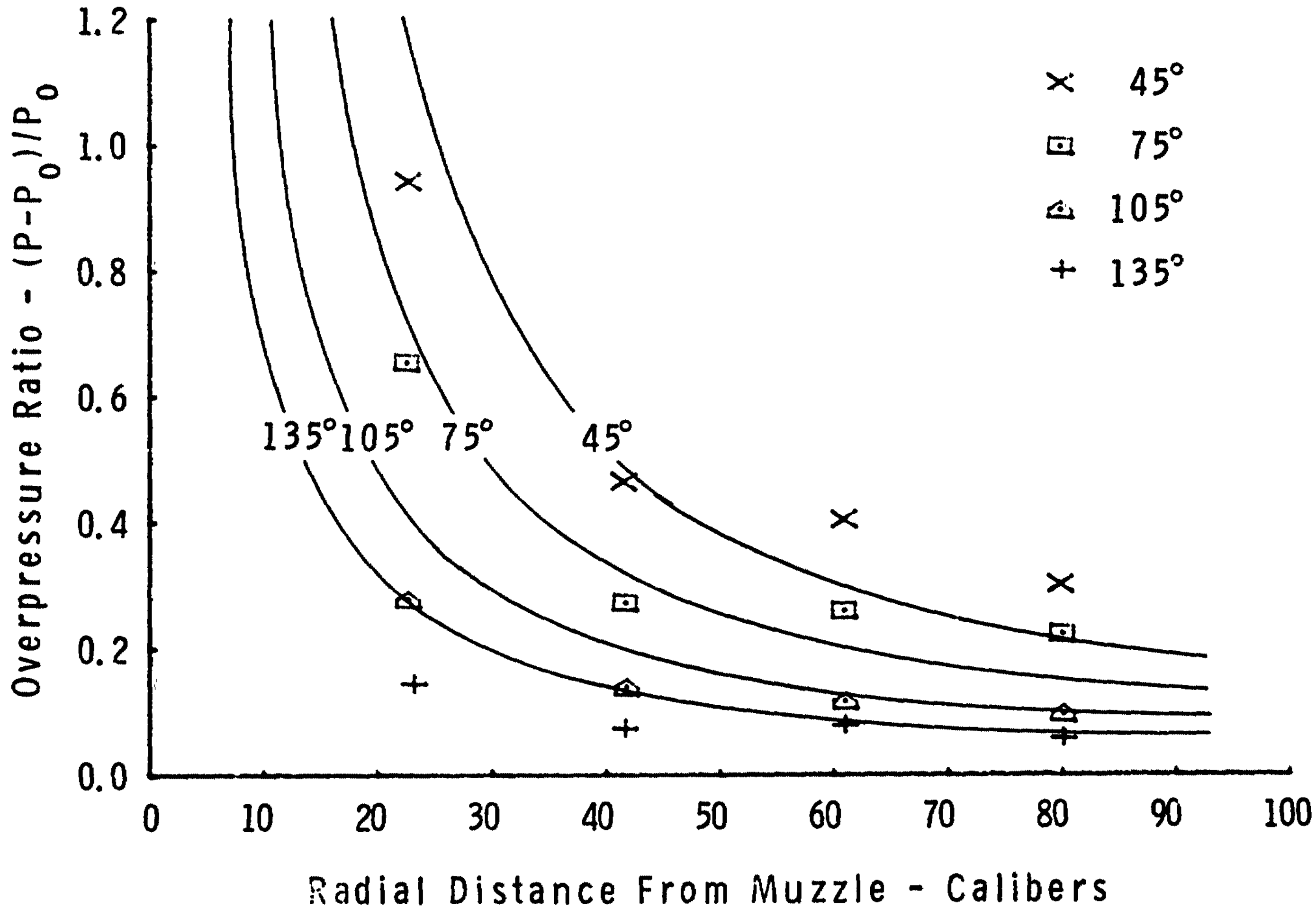

FIGURE 8. Overpressure from .30 Caliber Rifle.

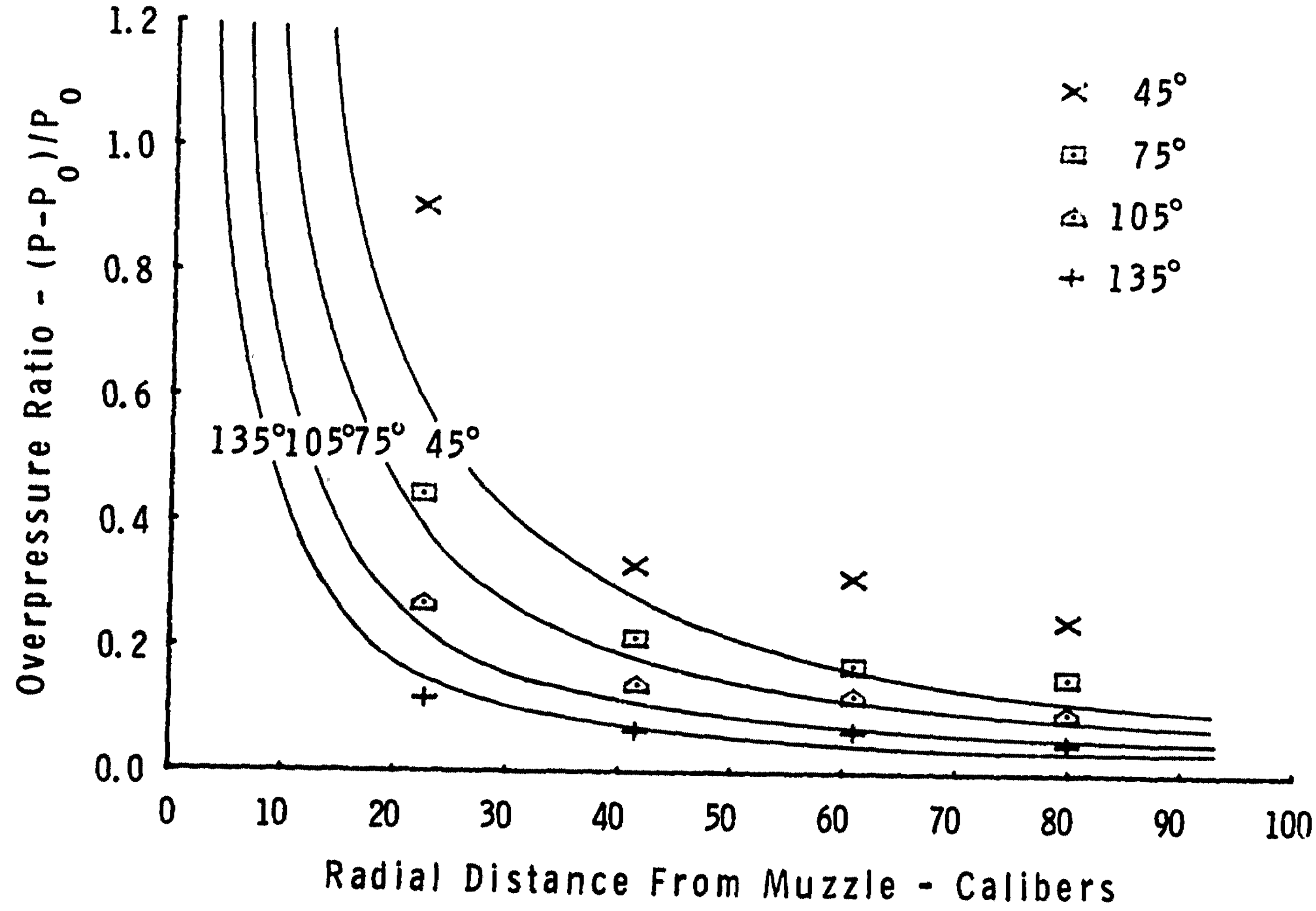

FIGURE 9. Overpressure from .30 Caliber Pistol.

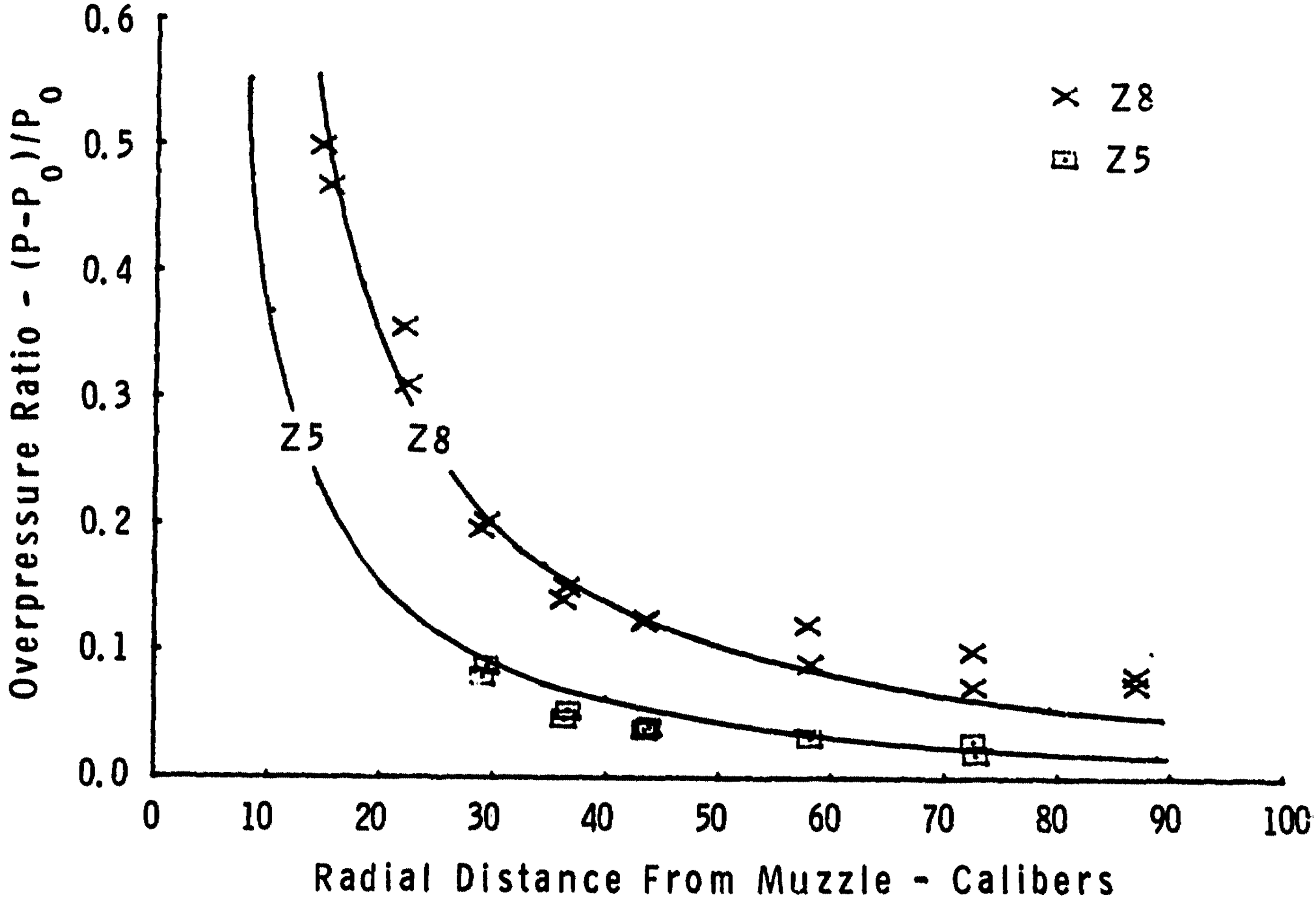

FIGURE 10. Overpressure from 105 mm Howitzer at Two Muzzle Velocities. Z8 is 650 m/s and Z5 is 332 m/s.

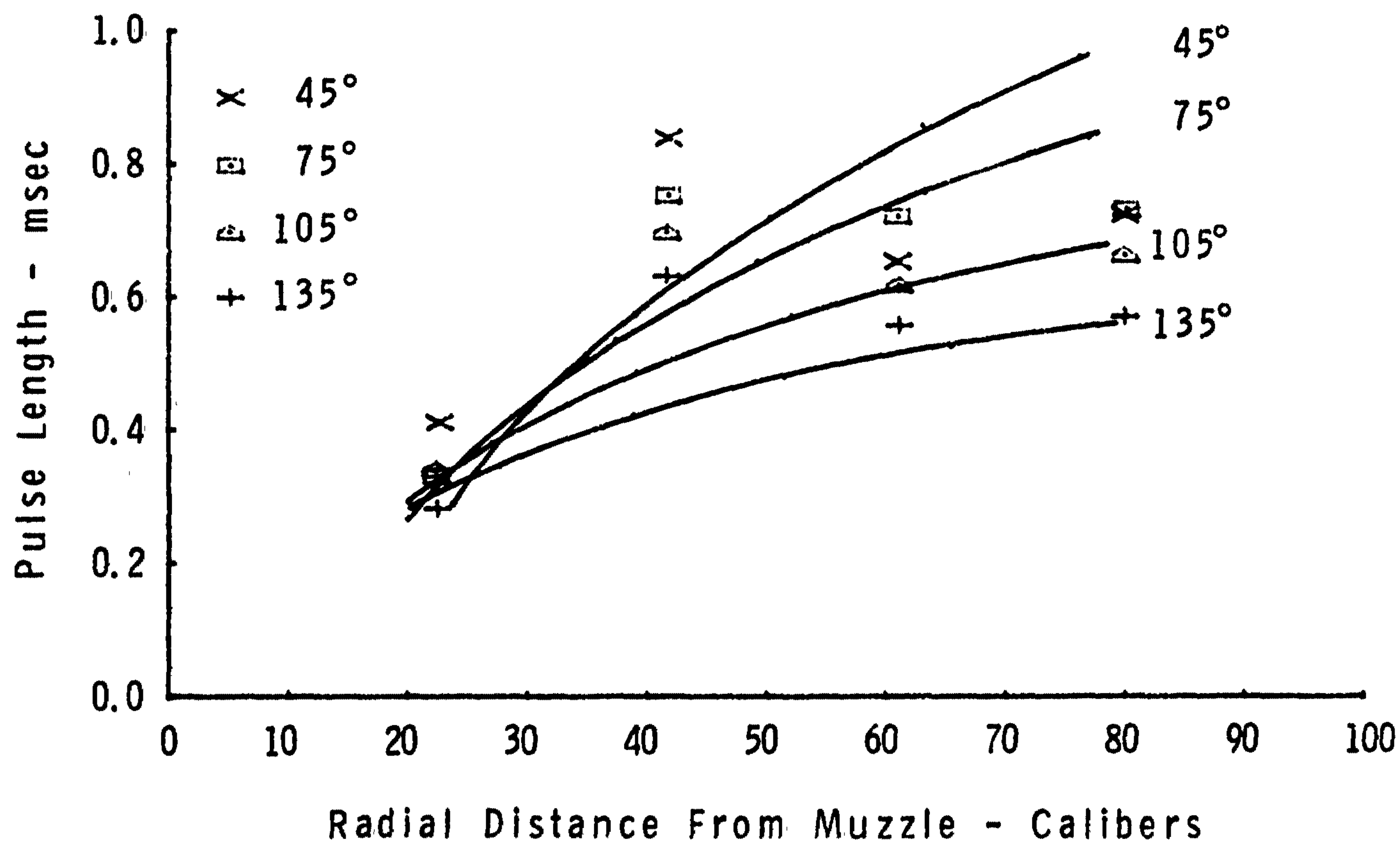

FIGURE 11. Overpressure Pulse Length from 20 mm Gun.

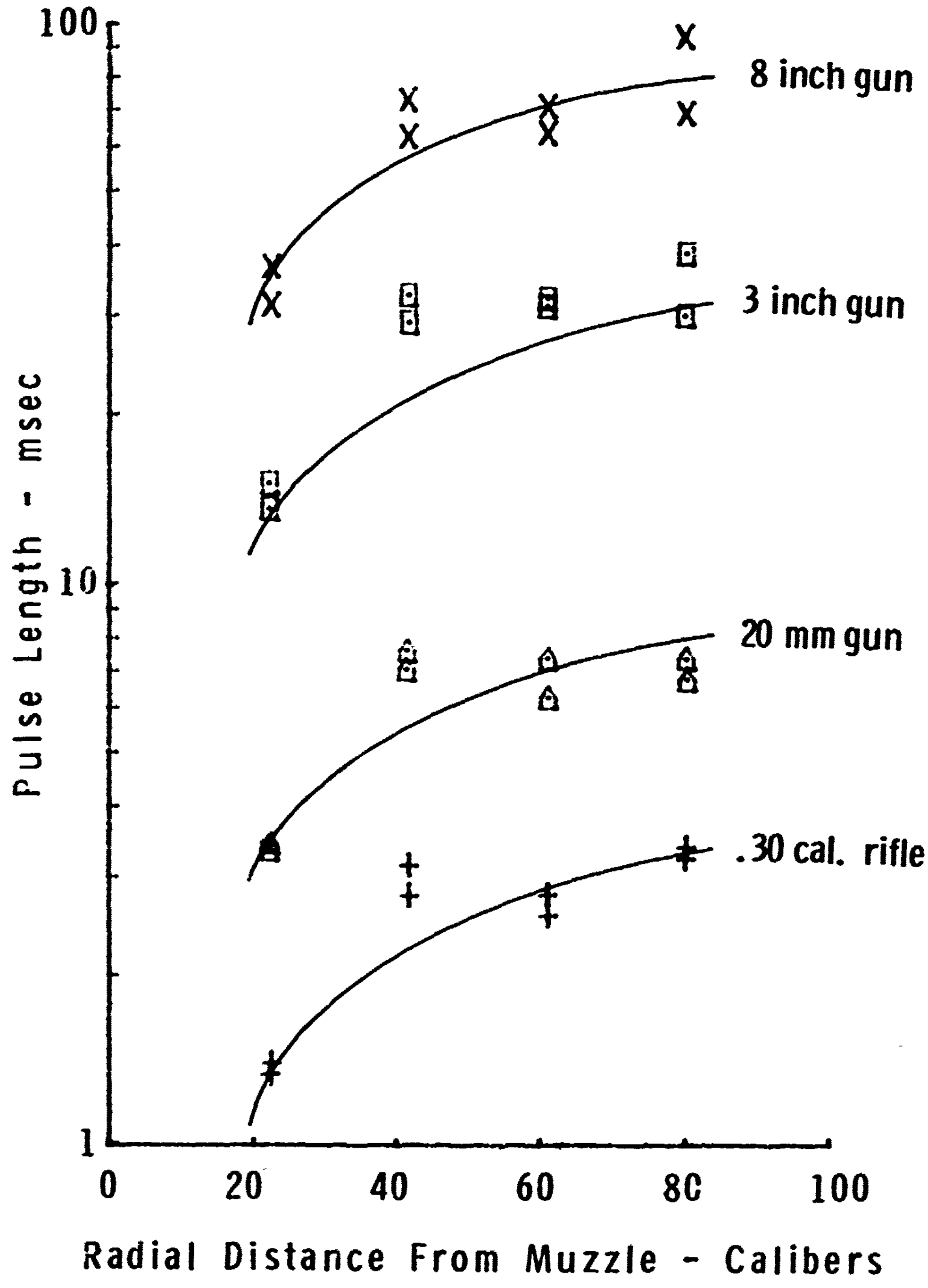

FIGURE 12. Overpressure Pulse Length for Four Guns.

APPENDIX A

The form of the geometry function $G(\theta)$ was developed on the basis of a moving charge. If the velocity at some point in the blast field is the sum of the charge velocity $\vec{V}_c$ and the blast velocity for a stationary charge $\vec{V}_s$ then $\vec{V} = \vec{V}_c + \vec{V}_s$ is assumed to be in the direction of the radius vector from the muzzle. If the field position is determined by the distance from the muzzle and the polar angle relative to the line-of-fire then θ is the angle between $\vec{V}$ and $\vec{V}_c$ and

$$V_s^2 = V^2 + V_c^2 - 2VV_c\cos\theta \tag{A1}$$

or

$$\left(\frac{V}{V_s}\right)^2 - 2\frac{V}{V_s}\,\frac{V_c}{V_s}\cos\theta + \left(\frac{V_c}{V_s}\right)^2 - 1 = 0 \tag{A2}$$

Solving for the ratio V/V_s we obtain

$$\frac{V}{V_s} = \frac{V_c}{V_s}\left\{\cos\theta \pm \sqrt{\cos^2\theta - \left[1 - \left(\frac{V_s}{V_c}\right)^2\right]}\right\} \tag{A3}$$

We assume that the geometry factor has a similar form ie.

$$G(\theta) = \alpha\left(\cos\theta + \sqrt{\cos^2\theta + \beta^2}\right) \tag{A4}$$

where α and β are constants to be determined.

If we require that at the angle $\theta=\pi/2$ the geometry factor have the value unity then

$$\beta = 1/\alpha \tag{A5}$$

Henricksen and Cummings[2] find that the kinetic energy of ordered motion at the muzzle is approximately twice that of random motion. Based on this result we require

$$G(0) = 2 \tag{A6}$$

This gives the results

$$\alpha = 3/4 \tag{A7}$$

and

$$G(\theta) = \frac{3}{4}\left[\cos\theta + \sqrt{\cos^2\theta + \left(\frac{4}{3}\right)^2}\right]. \tag{A8}$$

APPENDIX B

A BASIC computer program has been constructed to perform the calculations for the muzzle blast field based on the preceding analysis. The program is listed at the end of this appendix. The input parameters required for the program are as follows:

1. Projectile mass - kilograms (kg)
2. Muzzle velocity - metres/second (m/s)
3. Propellent specific energy - joules/kilogram (J/kg)
4. Ratio of peak chamber pressure to atmospheric pressure - dimensionless
5. Barrel length - metres (m)
6. Barrel diameter - metres (m)
7. Height of the barrel rifling - metres (m)

When execution of the program begins the program will pause for input until these values are entered in the order given above. When the last value is entered the program calculates the overpressure at the choke position and at the muzzle and an equivalent explosive yield. Next, the program will pause to allow optional values of Q1, Q2 and ratio of specific heats, γ to be entered if desired. The variables Q1 and Q2 are the exponents in the Porzel QZQ hypothesis for the strong and weak shock regimes and have the standard values 3.25 and 3.5 respectively. The standard value of γ is 1.4. After the option is exercised the program computes the transition radius and pauses until the desired angular position in the blast field is entered. This is the angle θ measured from the line of fire to the radius vector from the muzzle to the field location and lies between 0° and 180°.

The program is designed to calculate overpressure and pulse length as a function of distance from the muzzle at the input angle θ. The program will pause until the desired distance closest to the muzzle is entered. It then pauses until an increment in the radial distance is entered and again until the total number of increments desired is entered. The program then computes the overpressure and pulse lengths at each radial location specified for the angle θ specified. When these computations are completed the program pauses to allow the option of terminating the program or specifying another angle θ. If a new angle is entered then the program pauses to allow an option of continuing with the same radial locations or changing to new radial locations. When the last angular position desired has been calculated the operator enters minus one (-1) to terminate execution.

```
100   FOR N=1 TO 5 STEP 1
110   PRINT
120   NEXT N
140   PRINT "MUZZLE BLAST OVERPRESSURE AND PULSE LENGTH"
150   PRINT "-----------------------------------------"
160   PRINT
170   PRINT
200   REM . . . . INPUT SECTION . . . .
201   REM . . VARABLE DEFINITIONS ARE AS FOLLOWS:
202   REM . . PROJECTILE:  V0 - VELOCITY (M/SEC),  W0 - MASS (KG)
203   REM . . PROPELLANT:  W1 - MASS (KG),  X1 - SP. GRAVITY (KG/M**3)
204   REM . .              X2 - SPECIFIC ENERGY (J/KG)
205   REM . . PRESSURE:    P - CHAMBER PRESSURE RATIO (P/P0)
206   REM . . BARREL:     L0 - LENGTH (M),  D0 - DIAMETER (M),
207   REM . .              L1 - GROOVE HEIGHT (RIFLING) (M)
210   PRINT "PROJECTILE", "MASS (KG)",,
220   INPUT W0
225   PRINT
230   PRINT , "VELOCITY (M/SEC)",
240   INPUT V0
245   PRINT
246   PRINT
250   PRINT "PROPELLANT", "MASS (KG)",,
260   INPUT W1
265   PRINT
285   PRINT
290   PRINT, ,"SPECIFIC ENERGY (J/KG)",
300   INPUT X2
305   PRINT
306   PRINT
310   PRINT "CHAMBER PRESSURE RATIO (P/P0)",,
320   INPUT P0
325   PRINT
326   PRINT
PROCEED
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```
530  PRINT "BARREL",  "LENGTH (M)",,
540  INPUT L0
545  PRINT
550  PRINT ,"DIAMETER (M)",,
560  INPUT D0
565  PRINT
570 PRINT, "GROOVE HEIGHT (M)"
580  INPUT L1
590  PRINT
595  PRINT
400  REM . . END INPUT DATA
1000 REM . .
1010 REM . . BEGIN ENERGY CALCULATIONS
1011 REM . . E(PROP)=E2, E(PROJ)+E1, E(AVAIL)=E0
1020 LET E2=X2*W1
1030 LET E1=.5*W0*V0**2
1040 LET E0=E2-E1
1050 PRINT
1060 PRINT ,"   ENERGY CALCULATIONS"
1070 PRINT
1080 PRINT "TOTAL ENERGY IN PROPELLANT",,E2;"JOULES"
1090 PRINT "KINETIC ENERGY IN PROJECTILE",,E1;"JOULES"
1100 PRINT "MAXIMIM AVAILABLE ENERGY",,E0;"JOULES"
1110 LET PJ=PJ-1
2000 PRINT
2001 PRINT ,"   INTERIOR LOSSES"
2002 PRINT
2010 REM . . ROUGHNESS FACTOR=H, OVERPRESSURE RATIO AT CHOKE=Y
2020 REM . . O'PRESSURE RATIO AT MUZZLE AND INITIAL YIELD=Y0
2021 REM . . CHOKE LENGTH=L2
2030 LET H=L1/D0
2040 LET L2=0
2050 LET X=PJ
2060 REM . . IF CHOKE L/D>CUM L/D ASSUME NO CHOKE LOSSES
2065 IF H=0 GOTO 2100
PROCEED
```

BEST AVAILABLE COPY

```
2070  IF 15/H**.1>(L0/D0)GOTO 2100
2080  LET L2=15/H**.1
2090  REM . . IF P0>100 USE FITTED CURVE
2100  IF P0>100 GOTO 2160
2110  LET X=P0
2120  LET C=(1+X)*(1+4*X**2/5/(1+X)/(3+X))**5-1
2130  IF ABS (C-P0)<.001 GOTO 2170
2140  LET X=X-(X-1)*(C-P0)/(C-1.29)
2150  GOTO 2110
2160  LET X=EXP (.9211*LOG (P0)-2.135)
2170  PRINT "OVERPRESSURE RATIO AT";L2*D0;" M IS",X;"    (CHOKE)"
2180  LET Y0=EXP((2*H*(L2-L0/D0)+1.163* LOG (X))/1.010)
2190  PRINT "OVERPRESSURE AT";L0;" M IS",,Y0;"  MUZZLE"
2200  LET F=P0/Y0
2210  REM . . REDUCTION ME AVAILABLE
2220  LET Y0=E0/(6*F)
2230  LET E3 = W1/12*V0**2
2231  LET Y0=Y0+E3
2232  PRINT
2233  PRINT ,"   EQUIVALENT EXPLOSION PARAMETERS"
2234  PRINT
2240  PRINT "YIELD",,,Y0;" JOULES"
2250  LET R0=D0
2251  LET M0=W1/6
2252  FOR M=1 TO 5 STEP 1
2253  PRINT
2254  NEXT M
2260  PRINT "FOR OPTIONAL Q1,Q2,GAMMA ENTER ONE;STANDARD VALUES ENTER ZERO"
2261  INPUT O1
2262  IF O1=0 GOTO 2330
2270  PRINT "ENTER Q1"
2271  INPUT Q1
2272  PRINT "ENTER Q2"
PROCEED
```

```
2273  INPUT Q2
2274  PRINT "ENTER RATIO OF SPECIFIC HEATS,GAMMA"
2275  INPUT G
2276 GOTO 2500
2280  LET Q1=3.25
2281  LET Q2=3.5
2282  LET G=1.4
2300  REM ..Q0=PRESSURE/DENSITY(ATMOSPHERIC)
2301  LET Q0=78340
2302  LET H=.25
2303  LET Q5=1889
2304  LET P0=101325
2305  LET D=1.293
2310  LET M=Mu*H/5.416
2320  LET Z0=(R0**3+M)**(1/3)
2400  REM ..FIND TRANSITION RADIUS
2420  LET A1=(Q1-Q2)/(3-Q2)
2430  LET A2=(Q1-3)*Y0/(12.566*Q5*Z0**3)
2440  IF Q1=Q2 GOTO 2480
2450  LET Z=1
2451  LET S=Z
2452  LET F=A1*S**3-S**Q1+A2
2453  LET F1=3*A1*S**2-Q1*S**(Q1-1)
2454  LET Z=Z-F/F1
2455  IF ABS(Z-S)<.001 GOTO 2460
2456  GOTO 2451
2460  LET Z1=Z
2461  GOTO 2481
2480  LET Z1=A2**(1/Q1)
2481  LET R2=((Z1*Z0)**3-M)**(1/3)
2482  PRINT "TRANSITION RADIUS",R2,"METERS"
2500 REM ..SET UP QZQ CONSTANTS A AND B
2510  LET A=Q5/Q0*(Z1**Q1)
2520  LET B=Q5/Q0*Z1**Q2
PROCEED
```

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```
2550 PRINT
2560 PRINT
2590 REM ..SET UP DESIRED RADIAL LOCATIONS
2591 PRINT "INPUT ANGLE T1(DEGREES)"
2592 INPUT T1
2593 LET T2=COS(T1*3.14[illegible]/[illegible])
2595 LET R9=.75*(T2+SQR(T2*T2+[illegible]))
2596 PRINT "ENTER INITIAL RADIUS R3(METERS)"
2597 INPUT R3
2610 PRINT "INPUT RADIAL INCREMENT R4(METERS)"
2611 INPUT R4
2620 PRINT "INPUT NUMBER OF INCREMENTS DESIRED"
2621 INPUT K
2622 PRINT "RADIUS", "OVERPRESSURE","PULSE LENGTH"
2623 PRINT "(METERS)","(P-P0)/P0","(SECONDS)"
2624 PRINT "******","*************","************"
2625 LET S1=0
2626 LET C0=SQR(C*P0/D)
2627 LET T3=R2*R8/1000
2630 FOR I=1 TO K STEP 1
2640 LET R=(R3+R4*(I-1))
2650 FOR J=1 TO 10 STEP 1
2660 IF R<=R2*R8 GOTO 2700
2670 IF (R-R2*R8)<R4 GOTO 2700
2680 LET Y2=R4/10
2690 GOTO 2710
2700 LET Y2=(R-R2*R8)/1
2710 LET Y=(R-(10-J)*Y2)/R8
2720 GOSUB 4000
2730 LET U=(P1-1)*SQR(2*C0/((C+1)*P1+(C-1)))
2760 LET S1=S1+Y2/(1+(C+1)/[illegible]*U/C0)
2730 NEXT J
2740 LET T=T3+((R-R2*R8)-S1)/C0
2770 GOTO 2[illegible]
PROCEED
```

```
2780  LET T=T5
2785  LET V=R/R8
2790  GOSUB 4000
2800  LET P=P1-1
2810  PRINT R,P,T
2820  GOTO 2840
2830  PRINT "ERROR;RADIUS",R,"LESS THAN MUZZLE DIAMETER"
2840  NEXT I
3040  PRINT "INPUT NEXT ANGLE(DEGREES) OR NEG ONE TO TERMINATE"
3041  INPUT T1
3050  IF T1<0 GOTO 3070
3051  LET T2=COS(T1*3.14159/180)
3052  LET R8=.75*(T2+SQR(T2*T2+16/9))
3060  PRINT "ENTER ONE TO CHANGE RADIUS;ENTER ZERO TO CONTINUE"
3061  INPUT A8
3062  IF A8=0 GOTO 2625
3063  GOTO 2606
3070  PRINT "END OF UTE MUZZLE BLAST CALCULATIONS"
3080  GOTO 9999
4000  IF V<=R0 GOTO 2830
4010  LET Z=((V**3+M)**(1/3))/Z0
4020  IF Z <= Z1 GOTO 4060
4030  LET Q=B/(Z**Q2)
4040  LET Y1=Q0*Q/(Q2-3)*(Z0*Z)**3
4050  GOTO 4070
4060  LET Q=A/(Z**Q1)
4070  REM  ..NOW CALCULATE OVERPRESSURE
4080  IF Q <7.45E-7 GOTO 4210
4090  IF Q>1.167  GOTO 4310
4100  LET P1=5
4110  LET A1 = (G+1)/(G-1)+P1
4120  LET A2 = (G+1)/(G-1)*P1+1
4130  LET A3 = 1+(G-1)*Q
4140  LET F =A1*P1**(1/G)-A3*A2
PROCEED
```

```
4150 LET F1 = 1/G*A1*P1**(1/G-1)+P1**(1/G)
4160  LET F1 = F1-(G+1)/(G-1)*A3
4170  LET N=F/F1
4180  IF ABS(N)<.001 GOTO 4340
4190  LET P1=P1-N
4200 GOTO 4110
4210  LET P=.02
4220  LET C1=24*Q*G**3/(G+1)
4230  LET F=3*P**4-2*P**3+C1
4240  LET F1=12*P**3-G*P**2
4250  LET N=F/F1
4260  IF ABS(N)<.0005 GOTO 4290
4270  P=P-N
4280  GOTO 4230
4290  P1=P+1
4300  GOTO 4340
4310  LET K1=22+16*LOG(Q) /2.303
4320  LET L=11.5-SQR(132.25-K1)
4330  LETP1=10**L+1
4340  RETURN
9999  END
END OF WORK FILE
```